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Human-Ambient Interaction through Wireless Sensor Networks

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Abstract— **Recent developments in technology have permitted the creation of cheap, and unintrusive devices that may be effectively employed for instrumenting an intelligent environment. The present work describes a modular framework that makes use of a class of those devices, namely wireless sensors, in order to monitor relevant physical quantities and to collect users' requirements through implicit feedback. A central intelligent unit extracts higher-level concepts from raw sensory inputs, and carries on symbolic reasoning based on them. The aim of the reasoning is to plan a sequence of actions that will lead the environment to a state as close as possible to the users' desires, taking into account both implicit and explicit feedback from the users.**

I. INTRODUCTION

Systems for Ambient Intelligence (AmI) usually maintain a central role for the user, and they aim to reach the most favorable conditions for the users. This novel design paradigm relies on the capability of sensing the environment, extracting its relevant characteristics, and of controlling the environmental conditions through specialized actuators.

Wireless Sensor Networks (WSNs) allow for pervasive and unintrusive deployment of relatively cheap nodes, and are thus suitable for instrumenting an intelligent environment [1], [2]. They are made of a potentially large number of distributed computational units; those small sensor nodes are programmable, energetically autonomous, and able to wirelessly communicate with each other; moreover, they may be equipped with different sensors in order to measure the required physical quantities, and ad-hoc sensors may be devised for specialized tasks; for instance, sensor nodes may be integrated with sensors for IR signals, sensors for monitoring polluting agents, or RFId readers.

This papers describes an advanced approach to AmI, and describes the design of a modular framework that analyzes raw data sensed through a WSN, processes them in order to extract higher-level information, carries on symbolic reasoning on the inferred concepts, and produces the necessary actions to adapt the environment to the users' requirements. The proposed framework arranges lower-level components into an extensible architecture that implements an intelligent system for monitoring and controlling the environment where sensors are deployed. The lower level is represented by the sensory system permeating the environment, where sensed data are collected and pre-processed before being forwarded to the upper levels, where the actual intelligent processing occurs. Besides providing basic information about environmental conditions, the WSN allows to observe the interaction between the user and the surrounding environment, in order to model the users' actions, and to infer users' requirements about environmental conditions. According to the constructed model, the system will plan the sequence of actions to be performed in order to achieve the desired status; specialized actuators will act according to the derived rules. Our system also allows users to provide explicit feedback that will be used to refine and validate its reasoning.

This generic architecture may be easily specialized to improve the management of industrial, social, or home environments. This paper describes a case study regarding the management of a University Department premises; in this scenario, the main goal consists in accurately monitoring the ambient conditions of office rooms, and common spaces, and in taking proper actions that result in meeting the users' requirements, while satisfying energy constraints at the same time.

The remainder of the paper is organized as follows. Section II briefly describes other WSN-based or feedback-based approaches to AmI as reported in literature. Section III outlines the architecture of the proposed system, and Section IV describes the design of a prototype for a real scenario. Finally Section V gives some information about our on-going work.

II. RELATED WORKS

Many works presented in Ambient Intelligence literature make use of WSNs both as a distributed sensory tool, and as a wireless network infrastructure. However, to our best knowledge, none of them fully exploits the potential computational capabilities of the sensor nodes; rather they are typically used as a mere data collection tool, with distributed sensors and communication capabilities. In [3], [4], systems for healthcare are proposed, especially targeted to monitoring chronic illness, of for assistance to the elderly. Such works employ WSNs as the support infrastructure for biometrical data collection toward a central server; sensor nodes are thus required to simply route data packets through multiple hops without operating any distributed processing on them. In the work by Han, *et al.* [5], WSNs are used to provide inputs to an ambient robot system. Inside what the authors define a ubiquitous robotic space, a semantic representation is given to the information extracted from a WSN, but again this is used only as a sense-and-forward tool. In [6], a WSN-based infrastructure is described targeting the development of wildfire prevention system, whose architecture is based on

three layers, the lowest of which relies on a sensor network for measurement gathering. Also the work presented in [7] employs a WSN, but the goal is the collection of information about the occupancy of the monitored premises; collected data are aggregated in order to compute predictions about the occupant behaviour.

Several works on Ambient Intelligence exploit the capability of learning from the interaction with the surrounding environment, and with the user. In [8], a logical structure for an Ambient Intelligence system is proposed for the classification of events occurring in the considered environment, with the aim of facilitating intrusion detection. The classification step is based on an initial off-line training, based on a significant amount of training data, followed by an on-line phase, where a human operator provides explicit feedback about the quality of classification, so that the system may dynamically adapt its parameters. The same architectural scheme has been proposed in [9] and applied to the "classification of risk zones in a smart space"; the learning phase of the classifier is inspired here on the biological mechanisms that exploit memory of the past interactions between the intelligent entity and the other entities in the environment for learning. In [10], the authors propose an application of an unsupervised learning technique based on fuzzy logic to the intelligent agents constituting the Ambient Intelligence system. The fuzzy rules are learned by examining the users' behavior and are dynamically changed so that long-term goals may be satisfied. The inputs for the learning machine are gathered via the interactions between the user and the actuators allowing for manual environmental control.

Our proposal roughly resembles some of the previously cited works in that feedback from users is exploited in order to adapt the system behaviour. In particular, we devised a system based both on explicit feedback, similarly to what proposed in [8], [9], and on implicit feedback, similarly to [10], although none of them takes advantage of a pervasive sensory system such as the one we describe here.

III. System Architecture

The core of the entire architecture is represented by a centralized intelligent system that collects pre-processed data coming from the pervasive sensory system, carries on some reasoning in order to build an internal representation of the surrounding environment, and finally plans the proper actions taking into account both the internal representation and the goals derived from the users' requirements, as preliminarily described in [11].

The overall system is organized according to a layered architecture that allows to carry on specific reasoning on the environment at different levels of abstraction, and on different kinds of perceptions. From the designer's point of view, the layered organization allows for the realization of a scalable sofware architecture, able to effectively manage the huge amount of sensory data. This architecture implements a three-layer knowledge representation paradigm as in [12]; as shown in Figure 1, the lower subsymbolic layer deals with raw sensed quantities and provides only basic pre-processing,

and the higher symbolic layer provides a linguistic representation of knowledge; those two layers are connected through an intermediate layer where ground concepts are represented in a geometric space. The whole system is implemented on a central node with no strict resource constraints, with the exception of the subsymbolic tier that is localized on the WSN.

The WSN employed here is not used as a mere tool for data sensing and retransmitting, rather the computational resources of its constituting nodes are exploited; albeit limited, such capabilities may be effectively used to implement distributed algorithms for data filtering and aggregation. We propose a clustered network structure in which each small cluster, consituted by heterogeneous nodes with different computational capabilities, distributedly processes homogeneous data. This pre-processing phase exploits spatio-temporal correlation of data, in order to compute a model that nodes will share thanks to their cluster coordinator, similarly to the approach proposed in [13]. This process serves the two-fold purpose of reducing the number of unnecessary transmissions (only data not fitting the model will be transmitted in order to update the model itself), and of performing a dimensionality reduction that is used to preserve only relevant features.

Sensed measurements collected at the subsymbolic tier can be classified into two main categories, namely continuous or discrete; data belonging to the former class are fed to the intermediate conceptual layer, where they will be provided with a representation in terms of continuous quality dimensions. On the other hand, discrete data are outright handed over to the symbolic layer, where a linguistic representation will be given.

The conceptual tier is based on the idea of *conceptual spaces* introduced by Gärdenfors in [14]; data are endowed with a geometrical representation that allows for a straightforward management of the notion of concept similarity, as long as a proper metric is chosen for the quality dimensions. Points populating the conceptual space, originally generated by the underlying measurement space, are represented as vectors, whose components are the quality measurements of interest. Concepts thus naturally arise from the geometric space as regions, identifiable through an automated classification process, that in our implementation occurs after a supervised training of the classifier. The classifier is also devised so that it can dynamically adjust its internal representation of the concepts based on direct feedback provided by the user; a graphical interface will allow users to explicitly provide the system with an evaluation of the current conditions, so that it may adapt its classification engine to reflect the way users associate qualitative concepts to specific environmental conditions.

Finally, the symbolic tier produces a concise description of the environment by means of a high-level logical language. At this level, regions individuated inside the conceptual space are associated to a linguistic construct, thus identifying basic concepts, while relations necessary to infer more complex concepts are described through an opportune ontology. A
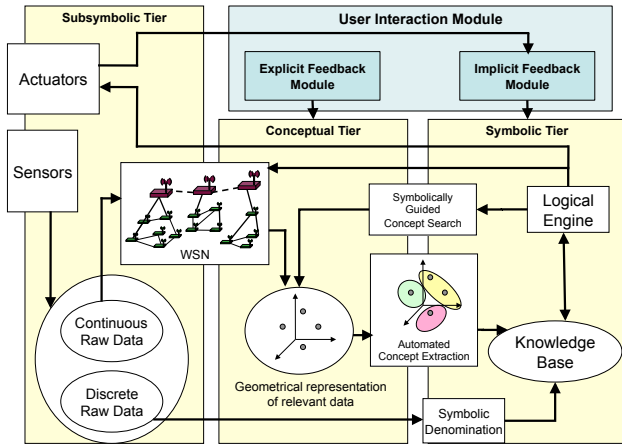
Fig. 1. The three-tier structure of the proposed system.

logical engine will operate on the knowledge base in order to trigger a set of actuators that will eventually modify the environment according to the system goals. Those devices may also be directly maneuvered by the user; the user's will of modifying the ambient conditions indicates that the current goal of the system is not completely satisfactory; by observing the users' actions, the system is able to obtain implicit feedback that may guide further planning. The WSN devoted to ambient monitoring also includes specialized sensors for perceiving the interactions of the users with the actuators, as will be detailed during the case study description.

IV. CASE STUDY

The system described here will be assessed by testing its behavior on a specific case study; the present section describes the specialization of the proposed architecture for an office environment, namely for the management of a University Department rooms. The goal of this specific prototype will include reasoning on such concepts as "air quality", "lighting conditions", or "room occupancy", taking into account the specific user's preferences, as well as energy consumption constraints. The sensory component of this system is implemented through a WSN, whose nodes are equipped with off-the-shelf sensors for measuring such quantities as indoor and outdoor temperature, relative humidity, and ambient light exposure; moreover, additional specific sensors may be installed on some nodes. For instance, RFId readers may be integrated on a few nodes in order to perform basic access control; also, simple software daemons may act as virtual "software sensors", and detect the users' activity on their workstations. As already explained, the system can adapt its planning in order to match the user's requirements, and as a consequence trigger the proper actuators controlling, for instance, the air conditioning, heating, and lighting systems, or the automated control of curtains; in the following, more details are provided about the sensor and actuator subsystems.

Our implementation makes use of MICAz nodes and Stargate microservers for the indoor WSN infrastructure; nodes have been deployed in various rooms close to "sensitive"

areas: by the door, by the window, and by the user's desk; additional nodes will be installed on the building facade, close to the office windows, for monitoring outdoor temperature, relative humidity, and light exposure. Comparing indoor and outdoor measurements may guide the selection of the more appropriate actions in some cases; for example, when indoor ambient light is not sufficient to ensure optimal working conditions according to the user's specifications, whereas outdoor sensors report a considerably higher value of light exposure, the system will conclude that the most efficient action in terms of energy saving would require activating the automated curtain control.

As regards more specific sensors, the present case study describes the integration of RFId readers into a few nodes of the WSN. Such readers enable automated identification of any object carrying an RFId tag, through wireless communication between the two devices; in case passive tags are employed, no independent energy source is required for their functioning, so that they are particularly suitable for use on everyday objects. In our prototype, RFId tags have been embedded into ID badges for the department personnel, while RFId readers are installed close to the main entrance and to each office door. Readings from each tag will be collected via their coupled nodes, and forwarded by the WSN to the intelligent core, that will process them and will reason about the presence of users in the different areas of the department. RFId-triggered reasoning about users' locations is inherently imprecise, but in our prototypal system it is integrated with additional information derived by the above mentioned "software sensors" that may signal the presence of the user at their desk.

The user may optionally decide to directly trigger any of the provided actuators; namely, the air conditioning, and automated curtain systems may be controlled via customized IR remotes, whose signals may be also sensed by the system that will infer a mismatch between the user's desires and the current environmental conditions, and act accordingly. The observation of those signals will be performed by the WSN itself, that will be enhanced with specific sensors; the resulting implicit feedback will represent the input of the learning process underlying the adaptive planning.

Besides implicit feedback collected via the sensor network, transparently to the user, our system includes a module for allowing users' direct interaction in the form of explicit feedback. In particular, the users may explicitly feed their assessment of the environmental conditions to the system through a graphical interface. By exploiting this information, the system may tune its classification engine to the users' evaluation. For instance, users may label air quality as "pleasant", "neutral", or "unpleasant", thus providing explicit grounding to the concepts of the geometric space, thus steering the classification process.

Finally, the overall energy consumption is also monitored via an ad-hoc sensor, that provides instantaneous information about active and reactive power, voltage and current. By analyzing specifically values related to active power, the intelligent subsystem will be able to tune and modify its

TABLE I

THE MAIN SENSORS USED IN THE PROTOTYPE AND THEIR CHARACTERISTICS.

Measure	Sensor	Characteristics
Temperature and relative humidity	Sensirion SHT11	Temperature range: -40 °F (-40 °C) to +254.9 °F (+123.8 °C) Temp. accuracy: +/- 0.5 °C @ 25 °C Humidity range: 0 to 100% RH Absolute RH accuracy: +/- 3.5% RH Low power consumption (typically 30 μW)
Barometric pressure and temperature	Intersema MS5534	Pressure range: 300 to 110 mbar Pressure accuracy: +/- 3.5% Temperature range: -10°C to 60°C Temperature accuracy: +/- 2°C Operating range 3.6 to 2.2 volts
Outdoor Light	Hamamatsu S1087	Si Photodiode with spectral response range λ: 320 – 730 nm Peak sensitivity wavelength λp 560 nm Photo sensitivity S (A/W) Infrared sensitivity ratio 10%
Ambient Light	Taos TSL2550	Range: 400 to 1000 nm Operating range 3.6 to 2.2 volts
RFId	LabId RWOSS	Standard ISO 15693 Reading range: ∼15 cm Microcontroller RISC 8 bit, Flash 32KB, RAM 2KB Interface: RS-232, USB

planned actions in order to satisfy some predefined energy consumption constraints; optionally, the user may be notified via the graphical interface.

V. CONCLUSION AND ON-GOING WORK

This paper described the structure of a modular framework for Ambient Intelligence exploiting Wireless Sensor Networks as a pervasive sensory system. WSNs are not merely used for data sensing and gathering purposes, rather their computational capabilities are effectively exploited in order to perform an initial preprocessing phase that constitutes the preliminary step for the overall reasoning. Besides providing basic information about environmental conditions, the WSN additionally allows to observe the interaction between the user and the surrounding environment, in order to infer users' requirements about environmental conditions. Users may also provide explicit feedback that will be used to refine and validate the system reasoning. The paper described a scenario where the system is employed in an office environment; currently, experiments are being carried on in order to test the basic behavior of the deployed WSN, and to collect a sufficient amount of data to be used to train the classifier of the intelligent system.

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